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Ecology, Design, and Long-Term Performance of Waste-Site Covers: Applications at a Uranium Mill Tailings Site

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Abstract

Conventional engineering approaches for designing covers for uranium mill tailings repositories fail to fully consider ecological processes that can have beneficial or deleterious effects on long-term performance. The U.S. Department of Energy developed an alternative design for the semiarid Monticello, Utah, Superfund site that combines fundamental ecological principles with the required engineered barriers (e.g., geomembranes, compacted soil layers). The design does not rely on compacted soils to control water infiltration, which can fail because of desiccation and cracking, but does rely on soil water retention enhanced by a capillary barrier and soil/plant evapotranspiration to seasonally return precipitation to the atmosphere. The design does not rely on rock riprap to control erosion, which can increase water infiltration and create habitat for deep-rooted plants, but does rely on a combination of vegetation and a simulated desert pavement to limit soil loss without influencing the soil water balance. The design controls radon releases, biointrusion, and protects critical layers from disturbance by frost. Preliminary analog studies of climate change, ecological change, and pedogenesis suggest that this design may improve with time. Field performance data and quantitative evaluations of analogs are needed before this alternative design is used without the redundant engineered barriers at other sites. Analog studies are needed to understand and evaluate possible long-term changes in the ecology of engineered covers that do not occur during short-term laboratory and field tests or that cannot be numerically modeled.

Introduction

The U.S. Department of Energy (DOE) is in the midst of cleaning up more than 20 million metric tons of low-level radioactive and sometimes chemically toxic tailings at abandoned uranium mills in the Four Corners region (Portillo 1992). The accepted remedial action is to cover tailings and other contaminated materials either in place or in landfill repositories. DOE faces the unprecedented legislative and engineering requirements that these tailings repositories persist for 200 to 1,000 years (EPA 1983). Engineered covers for tailings repositories typically consist of compacted soil layers, sand drains, and rock riprap intended to function as physical barriers to radon releases, water infiltration, and erosion (DOE 1989). This conventional engineering approach fails to fully consider the ecology of cover environments. After only a few years, biological disturbances threaten cover integrity at many sites (DOE 1992).

DOE developed an alternative cover design for the disposal of uranium mill tailings at the Monticello, Utah, millsite. This design is the product of unique combinations of regulatory and technical drivers. The Monticello repository design must satisfy both (1) minimum technology guidance (MTG) for hazardous waste disposal facilities (EPA 1989) under Subtitle C of the Resource Conservation and Recovery Act of 1976 (RCRA) and (2) design guidance for radon attenuation and 1,000-year longevity (DOE 1989) under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). This required engineering guidance was refined by incorporating some fundamental ecological principles. Our goal was to design a cover that will improve rather than degrade over the long term as inevitable natural processes act on the repository.

We summarize contaminant release mechanisms at uranium mill tailings repositories and then compare the design and intended functional performance of the Monticello cover with conventional RCRA and UMTRCA covers. Recommendations for design improvements, cost reductions, and assessment of long-term performance issues are also presented.

Contaminant Release Mechanisms

Several concomitant release mechanisms acting on the cover could potentially cause environmental transport of tailings contaminants.

Water Infiltration

Rainwater and snow melt not lost by runoff and evaporation will enter the rock and soil layers overlying the tailings and become distributed in the these materials in response to various water potential gradients (Hillel 1980). Depending on the properties and thicknesses of these layers, soil water could evaporate from the cover surface, be extracted by plants and returned to the atmosphere as transpiration, remain stored in the soil, pass into and remain stored in the tailings, or drain from the tailings and potentially mobilize and release contaminants.

Radon Release

Residual radioactive materials (radium-226) in uranium mill tailings emit radon gas. Rates of radon escape into the atmosphere above the repository will depend on the physical, hydrological, and radiological properties of the tailings and overlying soil layers. The properties that most influence radon release are the soil moisture content of the cover, the radon diffusion coefficient for the cover, radium-226 concentrations in the tailings, and the emanating fraction for radon in the tailings (Smith et al. 1985).

Erosion

Removal of fine-grained material by sheet-flow erosion, rilling, gullying, and wind deflation could expose and disperse tailings under extreme conditions or, more likely, reduce the thickness of overlying layers leading to contaminant transport by other pathways (e.g., water infiltration). Soil loss by sheet-flow erosion involves the detachment of soil particles from the cover by raindrop splash and overland flow. If storm runoff is intense, flow may concentrate and cut rills and gullies deep into the cover (Walters and Skaggs 1986). Wind transports soil particles by surface creep, saltation, and resuspension and may be particularly rapid leeward of topographic highs formed by mounded repositories (Ligotke 1994).

Frost Penetration

As temperatures drop and soil layers within the cover freeze, water drawn toward the freezing front can cause desiccation cracking (Chamberlain and Gow 1979), freeze/thaw cracking, and frost heaving (Miller 1980), particularly in compacted soil layers. Desiccation and frost cracking may lead to increased permeability and gas diffusion in compacted soil layers within the frost zone (Kim and Daniel 1992). Frost heaving may also cause distinct engineered soil layers to become mixed, thereby disrupting the integrity of critical layer interfaces (Bjornstad and Teel 1993).

Plant Root Intrusion

Plants growing in the cover could potentially root into tailings, actively translocating and disseminating contaminants in aboveground tissues (Foxx et al. 1984, Morris and Fraley 1989; Markose et al. 1993). Roots may also alter tailings chemistry potentially mobilizing contaminants (Cataldo et al. 1987). Macropores left by decomposing plant roots act as channels for water and gases to effectively bypass compacted soil barriers (Hillel 1980; Passioura 1991). Plant roots may concentrate in and extract water from buried clay layers, causing desiccation and cracking (Reynolds 1990). This water extraction can occur even when overlying soils are nearly saturated (Hakonson 1986), indicating that the rate of water extraction by plants may exceed the rehydration rate of the buried clay. Roots can also clog lateral drainage layers (DOE 1992), potentially increasing infiltration rates.

Animal Intrusion

Burrowing animals can mobilize contaminants by vertical displacement of tailings or by altering erosion, water balance, and radon-release processes (Hakonson et al. 1992). Vertical displacement results as animals excavate burrows and ingest or transport contamination on skin and fur (Hakonson et al. 1982). Once in the surface environment, contaminants may then be transferred through higher trophic levels and carried off site (Arthur and Markham 1983). Loose soil cast to the surface by burrowing animals is vulnerable to wind and water erosion (Winsor and Whicker 1980). Burrowing influences soil-water balance and radon releases by decreasing runoff, increasing rates of water infiltration and gas diffusion, and increasing evaporation because of natural drafts (Landeen 1994).

Cover Design and Performance

The Monticello cover (Figure 1) is structurally similar to the RCRA subtitle C design for hazardous-waste disposal facilities (EPA 1989). The seemingly subtle structural differences,

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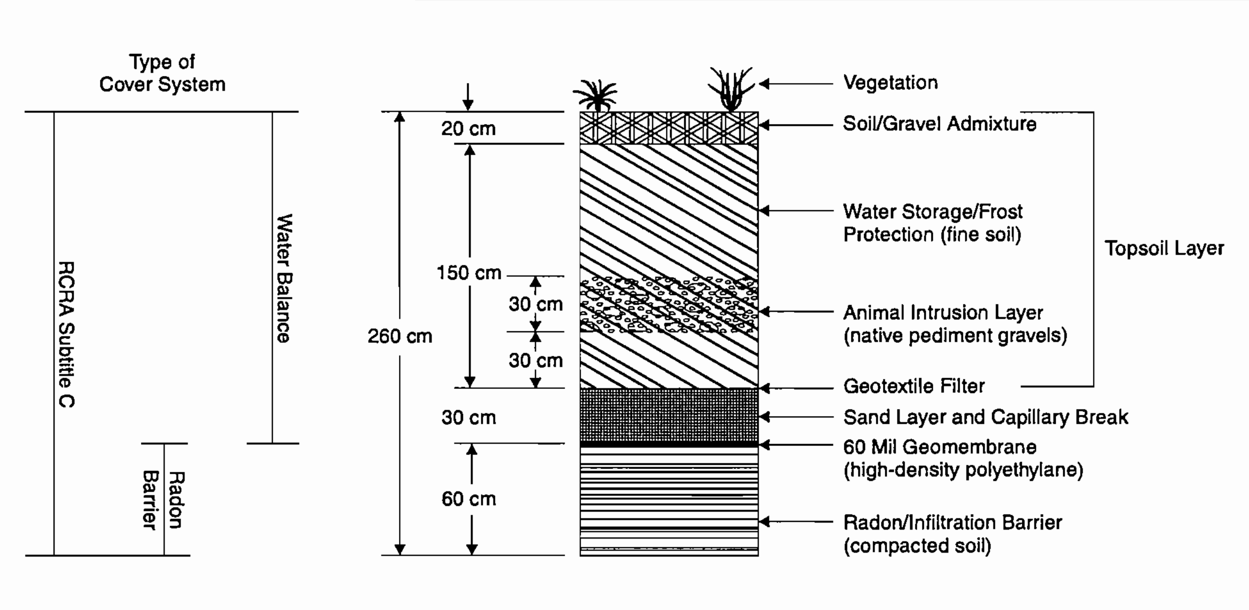

Figure 1. DOE Cover Design for the Monticello Repository

however, represent salient conceptual and functional differences in performance. Table 1 compares components of the Monticello and RCRA designs.

Water Infiltration Control

Water Balance System. Water infiltration and leakage through the cover must not exceed the leakage rate of the repository liner (EPA 1989). The Monticello repository liner includes a geosynthetic clay layer with a design permeability of 1 x 10^{-9} cm/s. The Monticello cover design for controlling water infiltration is essentially an MTG RCRA design (sand drainage layer, geomembrane, and compacted soil layer) but with a thicker topsoil layer. The reliance of RCRA and UMTRCA designs on low-permeability compacted soil layers is well documented (Daniel 1994; DOE 1989), and the failure of compacted soil layers to achieve performance objectives because of desiccation and shrinkage is also documented (Melchoir et al. 1994). The sand drainage layer, geomembrane, and compacted soil layer in the Monticello design serve as a backup for what we call a water-balance system. The water-balance system is the primary means for limiting infiltration over the long term.

At the semiarid Monticello site, groundwater recharge is naturally limited where thick loess soils store precipitation until soil evaporation and plant transpiration seasonally return it to the atmosphere (Waugh and Link 1992). The Monticello water-balance design includes a sand capillary break that enhances this natural water conservation. In accordance with the "outflow law" of soil physics (Richards 1950), the capillary barrier limits downward water movement and

Table 1. Comparison of RCRA Subtitle C (EPA 1989) and DOE MRAP Cover Designs

RCRA Subtitle C Cover	DOE Monticello Cover
Vegetation consists of locally adapted perennial plants selected for erosion control	Vegetation consists of locally adapted perennial plants selected for erosion control and soil-water extraction
No gravel admixture layer	Soil/gravel admixture layer to enhance erosion control without adversely influencing plant water extraction • 20 cm thick • 40% by weight sand and gravel • 2- to 6-cm diameter gravel
Top slope between 3% and 5%	Top slope between 3% and 5%
Topsoil layer • 60 cm thick • Fine-textured soil (e.g., loams)	Topsoil layer • 170 cm thick • Fine-textured soil (silt loam to sandy clay loam)
No animal intrusion barrier	30-cm-thick animal intrusion barrier consists of gravels and cobbles placed within the topsoil layer
Soil or geotextile filter as layer separator	Geotextile filter as layer separator
30-cm screened sand drainage layer • K_{sat}[a] = 1×10^{-2} cm/s • 10-mm maximum particle size • Slope ≥ 3%	30-cm screened sand drainage layer • $K_{sat} = 1 \times 10^{-2}$ cm/s • 10-mm maximum particle size • Slope ≥ 3%
Geomembrane ≥ 0.5 mm thick	60-mil high-density polyethylene geomembrane
Compacted, low-permeability soil layer • 60 cm thick • $K_{sat} \leq 1 \times 10^{-7}$ cm/s	Compacted, low-permeability soil layer • 60 cm thick • $K_{sat} \leq 1 \times 10^{-7}$ cm/s

[a] K_{sat} = saturated hydraulic conductivity.

increases the water storage capacity of the topsoil layer because high tensions (suction) in the small pores of the topsoil impede movement of water into the larger pores of the underlying sand layer. Leakage into the sand occurs only if water accumulation at the topsoil/sand layer interface approaches saturation and tensions decrease sufficiently for water to enter the large pores of the sand layer (Hillel 1980). The geotextile filter maintains the fine/coarse layer discontinuity until soil aggregation occurs by natural pedogenic processes (Bjornstad and Teel 1993). Evapotranspiration can prevent excessive water accumulation above the textural break (Waugh et al. 1991; Anderson et al. 1993; Link et al. 1994). In short, the topsoil stores water while plants are dormant, then plants extract stored water during the growing season and return it to the atmosphere.

Leakage from the water-balance system is evaluated as the probability that water accumulation rates will exceed evapotranspiration and, eventually, the water storage capacity of the topsoil layer. Soil-water storage capacity is the difference between the upper storage limit (before leakage occurs), sometimes referred to as the field capacity, and the lower storage limit (after removal of plant extractable water) (Ritchie 1981). Field-plot and lysimeter tests conducted at other DOE sites (Waugh et al. 1991; Wing and Gee 1993; Anderson et al. 1993) suggest that, with plants present to seasonally dry the Monticello cover, water accumulation will not likely exceed the topsoil storage capacity, even during higher than record precipitation years. Field and modeling studies are ongoing at Monticello to test this hypothesis. Preliminary results corroborate results of the previous studies. For the next generation of DOE cover designs, a water-balance system without redundant geomembranes and compacted soil layers may be adequate to control water infiltration at arid and semiarid sites.

Revegetation. The calculated thickness of the Monticello topsoil not only provides an optimum water-balance system but also creates a habitat more suitable for desirable vegetation. A thinner layer would encourage the establishment of a woodland plant community consisting of undesirable deep-rooted species. A diverse mixture of native plants on the cover will maximize water removal by evapotranspiration (Link et al. 1994) and remain more resilient to catastrophes and fluctuations in the environment (Begon et al. 1986).

Revegetation activities will attempt to emulate the structure, function, diversity, and dynamics of native plant communities in the area. The native sagebrush-grass vegetation at Monticello is a mosaic of many species that structurally and functionally changes in response to disturbances and environmental fluctuations (Tausch et al. 1993). Similarly, biological diversity in the cover vegetation will be important to community stability and resilience, given variable and unpredictable changes in the environment resulting from pathogen and pest outbreaks, disturbances (overgrazing, fire, etc.), and climatic fluctuations. Local indigenous genotypes that have been selected over thousands of years are best adapted to climatic and biological perturbations. In contrast, exotic grass plantings, common on waste sites, are genetically and structurally monotonous (Harper 1987) and, thus, more vulnerable to disturbance or eradication by single factors.

Radon Attenuation

The 60-cm compacted soil layer (radon/infiltration barrier in Figure 1) satisfies the requirement for a radon barrier that limits the average surface flux of radon-222 to less than 20 pCi m^{-2} s^{-1} (EPA 1983). The thickness was calculated with the standard method—the U.S. Nuclear Regulatory Commission (NRC) model RADON (NRC 1989). This design approach is documented elsewhere in DOE (1989). As required for UMTRCA sites (NRC 1989), only the compacted soil layer (radon/infiltration barrier) of the cover was included in this calculation. All overlying layers were omitted. Further analysis suggests that the compacted soil layer may be unnecessary. RADON model results show a lower radon flux from a cover consisting of only a water-balance system.

Erosion Control

The primary erosion control issue is will vegetation alone adequately limit soil loss or are gravel mulches, gravel admixtures, or rock riprap necessary to armor the soil when vegetation is sparse or less dependable. Vegetation and organic litter disperse raindrop energy, slow flow velocity, bind soil particles, filter sediment from runoff, increase infiltration, and reduce surface wind velocity (Wischmeier and Smith 1978). Vegetation may be inadequate in the first years after construction. UMTRCA and alternative RCRA designs include cobble or rock riprap to control erosion in arid environments with sparse vegetation (DOE 1989; EPA 1989). However, these designs reduce evaporation (Groenevelt et al. 1989; Kemper et al. 1994), possibly increasing leakage through compacted soil layers and creating habitat for undesirable plants that root into the radon/infiltration barrier (DOE 1992).

Erosion control for the Monticello design consists of mixing gravel and sand in the top 20 cm of the topsoil (Figure 1) to mimic conditions leading to the formation of desert pavement. The method of Temple et al. (1987) was used to size the gravel (Table 1). The sand component was sized relative to the topsoil and gravel with Stephanson's (1979) method. Several erosion studies (Finely et al. 1985; Ligotke 1994) and soil-water balance studies (Waugh et al. 1994b; Sackschewsky et al. 1995) suggest that moderate amounts of gravel mixed into the cover topsoil will control both water and wind erosion with little effect on plant habitat or soil-water balance. As wind and water pass over the surface, some winnowing of fines from the admixture is expected, leaving a vegetated erosion-resistant pavement. The sand "filter" and root cohesion of fines will impede continued soil loss beneath this pavement (Styczen and Morgan 1995). The combination of vegetation and gravel pavement will control sheet flow, minor rilling, and wind erosion by decreasing tractive sheer stresses. Rilling and gullying is controlled by maintaining top-slope gradients equal to surrounding terrain (which lack rills and intermittent gullies) and by limiting lengths of overland flow paths.

Frost Protection

The 170-cm composite topsoil layer (Figure 1) provides more than adequate depth to isolate the capillary break layer, drainage layer, geomembrane, and compacted soil layer (radon/infiltration barrier) from frost damage. The estimated maximum frost depth for a 200-year return interval in the topsoil layer is 115 cm. This value was extrapolated from soil physical properties for the loess soil and Monticello weather data by using the modified Berggren equation presented in DOE's *Technical Approach Document* (DOE 1989). UMTRCA rock riprap covers have essentially no frost protection for the radon infiltration barrier, and the 60 cm of frost protection offered by the RCRA cover is inadequate for Monticello.

Biointrusion Control

The Monticello cover includes barriers to biological intrusion by plant roots and burrowing vertebrates. By retaining soil water close to the surface, the combined topsoil and capillary barrier create a habitat for relatively shallow-rooted plant species and, thus, function as a de facto root-intrusion barrier (Cline et al. 1980; Hakonson 1986). Root growth is generally limited to regions within the soil where extractable water is available. The compacted soil layers in RCRA and UMTRCA covers may offer some protection. Agronomists have long observed that highly compacted soils cause stubby and gnarled root growth (Passioura 1991) and can reduce rooting depths (Foxx et al. 1984). However, plants vary greatly in their ability to penetrate compacted soils (Materechera et al. 1991). At arid and semiarid sites, root densities can be higher in buried clay layers and cause seasonal desiccation (Hakonson 1986; Reynolds 1990).

The composite topsoil layer thickness is also the primary barrier to burrowing; it exceeds the maximum burrow depths of most vertebrates at Monticello. The 30-cm layer of native pediment gravel within the composite topsoil layer is an added deterrent. Loosely aggregated gravel and rock have been shown to deter burrowing mammals (Cline et al. 1980; Hakonson 1986). This layer is above and protects the capillary break from bioturbation, a primary long-term threat to layer systems (Bjornstad and Teel 1993). The native pediment gravels contain enough fines to prevent this layer from behaving like a secondary capillary barrier.

Longevity

The greatest uncertainties in designing the Monticello cover stem from the scientifically challenging need to extrapolate the results of short-term tests to the required 200- to 1,000-year performance period. Standard engineering approaches that are based on laboratory tests, short-term field demonstrations, and numerical predictions implicitly assume that initial conditions of material properties and of processes that drive contaminant transport will persist. In contrast, engineered covers must be viewed as evolving components of larger, dynamic ecosystems.

Natural analogs provide clues from past environments to possible long-term changes in engineered covers (Waugh et al. 1994a). Logical analogy is used to investigate natural and archaeological occurrences of materials, conditions, or processes that are similar to those known or predicted to occur in some part of the engineered cover system. As such, analogs can be thought of as uncontrolled, long-term experiments. Analogs may also have a role in communicating the results of the performance assessment to the public. Evidence from natural systems can help demonstrate that numerical predictions have real-world complements. Long-term performance issues at Monticello that can be assessed with the use of analogs include climate change, ecological change, and pedogenesis (soil development).

Climate Change. Climate greatly influences the release of hazardous materials from buried tailings at Monticello and the performance of the engineered cover designed to isolate tailings. With evidence of relatively rapid past climate change (Crowley and North 1991) and model predictions of global climatic variation exceeding the historical record (Ramanathan 1988), DOE recognizes a need to incorporate possible ranges of future climatic and ecological change in the repository design process (Petersen et al. 1993). Paleoclimatic records may be useful not only as a window on the past but also as analogs of possible local responses to future global change.

We reconstructed past climate change for Monticello by using available proxy data from tree rings, packrat middens, lake sediment pollen, and archaeological records (Waugh and Petersen 1995). Interpretation of proxy paleoclimatic records was based on present-day relationships between plant distribution, precipitation, and temperature along a generalized elevational gradient for the region. For Monticello, this first approximation yielded mean annual temperature and precipitation ranges of 2 to 10 °C, and 38 to 80 cm, respectively, corresponding to late glacial and Altithermal periods. These data are considered to be reasonable ranges of future climatic conditions that can be input to evaluations of water infiltration, radon-gas escape, erosion, frost penetration, and biointrusion.

Pedogenesis and Ecological Change. Pedogenic processes will gradually change the physical and hydraulic properties of earthen materials used to construct the Monticello cover (e.g., McFadden et al. 1987; Hillel 1980). Plant and animal communities inhabiting the cover will also change in response to climate and disturbances. As the ecology of the cover changes, so also will performance factors such as water infiltration, evapotranspiration, water retention, soil loss, radon diffusion, and biointrusion.

Weighing lysimeters encasing 100-cm-deep soil monoliths were installed near the proposed Monticello repository site to measure the water balance of analog soils and vegetation (Waugh and Link 1992). Monolithic lysimeters preserve, as well as possible, native soil profiles and vegetation. All precipitation received during the 1991 and 1992 bioclimatic years (November through October) was retained (no leakage occurred); close to normal precipitation was received for both years. Approximately 2.8 cm of leakage was measured during spring of 1993, indicating that soil-water accumulation exceeded the storage capacity that year. The 1992–1993 winter (December–February) was one of the wettest on record (315 percent of normal); Monticello experienced the wettest February of this century. The increased storage capacity of a 170-cm soil layer over a capillary break would likely have retained all the excess soil water. These results suggest that with plants present to seasonally dry the topsoil layer of the cover, water accumulation will not likely exceed the topsoil storage capacity, except during years with higher than record precipitation.

Summary

DOE plans to construct a lined landfill for disposal of tailings from an abandoned uranium mill at Monticello, Utah. The cover design, although similar in appearance, represents a departure from typical RCRA and UMTRCA designs. These typical designs are vulnerable to natural processes that will degrade the cover over the long term. In contrast, the DOE design for the Monticello cover relies on the same natural processes to isolate tailings and to control the release of contaminants but is expected to improve over time.

The Monticello design should be considered as an alternative to RCRA Subtitle C and UMTRCA designs at other arid and semiarid sites:

- Compacted soil layers, as required for RCRA and UMTRCA designs to control water infiltration, are vulnerable to damage by desiccation and biointrusion. In contrast, the Monticello water-balance cover relies on soil-water retention, capillary barriers, and soil-water extraction by plants.

- Rock riprap layers, as recommended for UMTRCA designs, control erosion, enhance water infiltration, and biointrusion. The Monticello design includes a topsoil and gravel admixture. Over time, the admixture is designed to control erosion much like a desert pavement without adversely influencing desirable vegetation and the soil-water balance.
- The Monticello design includes a geomembrane and a compacted soil layer as redundant infiltration barriers and to control radon release. These layers are also required to meet RCRA and UMTRCA design requirements. Results of small-scale field tests and numerical modeling suggest that the water-balance cover will satisfy performance standards for water infiltration and radon releases without the engineered barriers.
- Field monitoring of water balance, erosion, and biointrusion are needed to evaluate the performance of the Monticello design under realistic conditions, before the design is used at other sites without the redundant engineered barriers. Similar measurement in natural analog environments may provide clues about long-term performance.

Engineered covers that are intended to last hundreds and thousands of years must be designed as evolving components of larger dynamic ecosystems. Four tenets accompany this principle: (1) cover components will not function and, thus, cannot be designed independently; (2) physical and ecological conditions will change over time, therefore, initial conditions cannot be extrapolated as tests of long-term performance; (3) designs should not rely on man-made materials of unknown durability; and (4) the design should not rely on physical barriers to natural processes but on the use of natural processes.

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